Beam dynamics design for uranium drift tube linear accelerator *

DOU Wei-Ping(窦为平)[1,2] HE Yuan(何源)[1] LU Yuan-Rong(陆元荣)[3;1)]

[1] Institute of Modern Physics, China Academy of Sciences, Lanzhou 730000, China
[2] University of Chinese Academy of Sciences, Beijing 100049, China
[3] State Key Lab of Nuclear Physics and Technology, Peking University, Beijing 100847, China

Abstract: KONUS beam dynamics design of uranium DTL with LORASR code is presented. The $^{238}U^{34+}$ beam, whose current is 5.0 emA, is accelerated from injection energy of 0.35 MeV/u to output energy of 1.30 MeV/u by IH-DTL operated at 81.25 MHz in HIAF project at IMP of CAS. It achieves a transmission efficiency of 94.95% with a cavity length of 267.8 cm. The optimization aims are the reduction of emittance growth, beam loss and project costs. Because of the requirements of CW mode operation, the designed average acceleration gradient is about 2.48 MV/m. The maximum axial field is 10.2 MV/m，meanwhile the Kilpatrick breakdown field is 10.56 MV/m at 81.25 MHz.

Key words: drift tube linear accelerator, beam dynamics, high gradient, continuous wave

PACS: 29.27.Bd, 41.85.Ja, 42.60.Da **DOI:** 10.1088/1674-1137/38/7/077001

1 Introduction

HIAF is a high intensity accelerator facility at IMP of CAS. HISCL is a high intensive heavy ion superconducting linear accelerator that is used as the injector of HIAF. It consists of an ion source LEBT, RFQ, MEBT, and a superconducting linear accelerator. It provides protons to the uranium beam of 25 MeV/u for the synchrotron. Up to now, the RFQ beam dynamics has been designed with DESRFQ [1] code, which is developed by ITEP (Institute for Theoretical and Experimental Physics), especially for the RFQ with an external buncher. Several QWRs were planned to accelerate the beam from an energy of 0.35 MeV/u to 1.3 MeV/u. Because of the high shunt impedance of IH-DTL [2, 3] for the low β particles, a normal conducting IH-DTL cavity based on KONUS [4–6] beam dynamics is proposed to replace the original QWRs in order to shorten the length of accelerators and decrease the manufacturing cost.

KOmbinierte NUll grad Struktur（KONUS）beam dynamics, which means “Combined Zero Degree Structure”, can well overcome the conflict of transverse defocusing, longitudinal bunching and accelerating of RF fields. Many projects, such as GSI High Charge State Injector (HLI) [7], High Current Injector (HSI) [8, 9], and Heidelberg Therapy Injector [10], have been designed, manufactured and operated successfully by using KONUS beam dynamics. These projects show that IH-DTL for low β ions has very high accelerating gradient.

A KONUS period consists of a quadruple triplet, a rebuncher section with traditional negative synchronous phase, and a multi cell acceleration section with zero degree synchronous phase. KONUS beam dynamics simulation is coded to LORASR，which is abbreviated from German “LOngitudinale und RAdiale Strahldynamikrechnungen mit Raumladung” [11]. In a normal linear accelerator, the synchronous particles with 0° will have a maximum kinetic energy gain but the stable phase range becomes zero. When a bunch center phase is injected at a bit positive the radial motion is focused and the longitudinal motion is defocused. Bunched particles have less energy gain than zero degree synchronous phase particles. If they have a bit higher injection energy, then they will arrive at the accelerating gap slightly earlier than RF ramping; that is, bunched center phase moves from positive to negative phase gradually. So, the radial motion moves from focusing to defocusing. Meanwhile, the longitudinal motion moves from defocusing to focusing. More zero degree synchronous phases are set until the accumulated radial defocusing needs to be compensated by the quadruple lenses. After the introduction of quadruple lenses，because of the beam energy spread，longitudinal motion needs to be rebunched at the beginning of each KONUS section.

2 The IH-DTL simulation results of LORASR

The input twiss parameters for LORASR are listed

Received 5 August 2013
∗ Supported by NSFC (11079001)
1) E-mail: yrlu@pku.edu.cn

in Table 1. Phase advance per structure period is shown in Fig. 1. The transmission efficiency is simulated for the uniform particle distributions with the above twiss parameters. Actually, it is almost 100% for the Gaussian particle distribution because more particles are concentrated in the core center of input elliptical distribution. The input and exit particles distributions are shown in Fig. 2. The design of RFQ is under optimization and MEBT is used to match beam parameters from exit of RFQ to entrance of IH-DTL. A converging beam with big size and small angle is needed for better beam transmission.

Table 1. The input tiwss parameters.

input twiss parameters	α	$\beta/(\text{mm}\cdot\text{mrad}^{-1})$	$\varepsilon_{\text{n.rms}}/(\text{mm}\cdot\text{mrad})$
x	0.9064	0.5567	0.2041
y	0.9636	0.5005	0.2024
z	0.3188	0.3989	0.1228

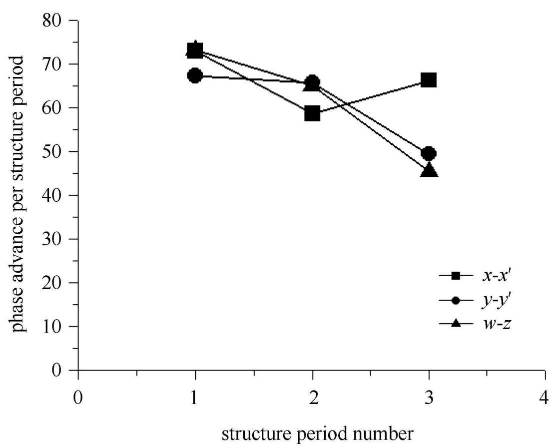

Fig. 1. Phase advance per structure period.

The energy spreads and synchronous phases at every accelerating gap for different KONUS sections (for any particle index as “c”, synchronous particle index as “s”) are shown in Fig. 3. Conventional negative synchronous phase sections are needed in front of zero degree sections (Fig. 3, position ‘a’) to keep the longitudinal motion focused. When the particles passes through the first gap of zero degree sections (Fig. 3, position ‘b’, ‘d’ and ‘f’), the bunched center phase is a bit positive. Radial motion is focused and longitudinal motion is defocused. But bunched center particles have a bit higher injection energy. They will arrive at the accelerating gap slightly earlier than RF ramping; that is, the bunched center phase moves from positive to negative phase gradually. At exit (Fig. 3, position ‘c’, ‘e’ and ‘g’), the longitudinal motion is focused and radial motion is defocused. The longitudinal (Fig. 4(a) and 4(b)) and transverse (Fig. 4(c) and 4(d)) beam 100% envelopes for the design current of

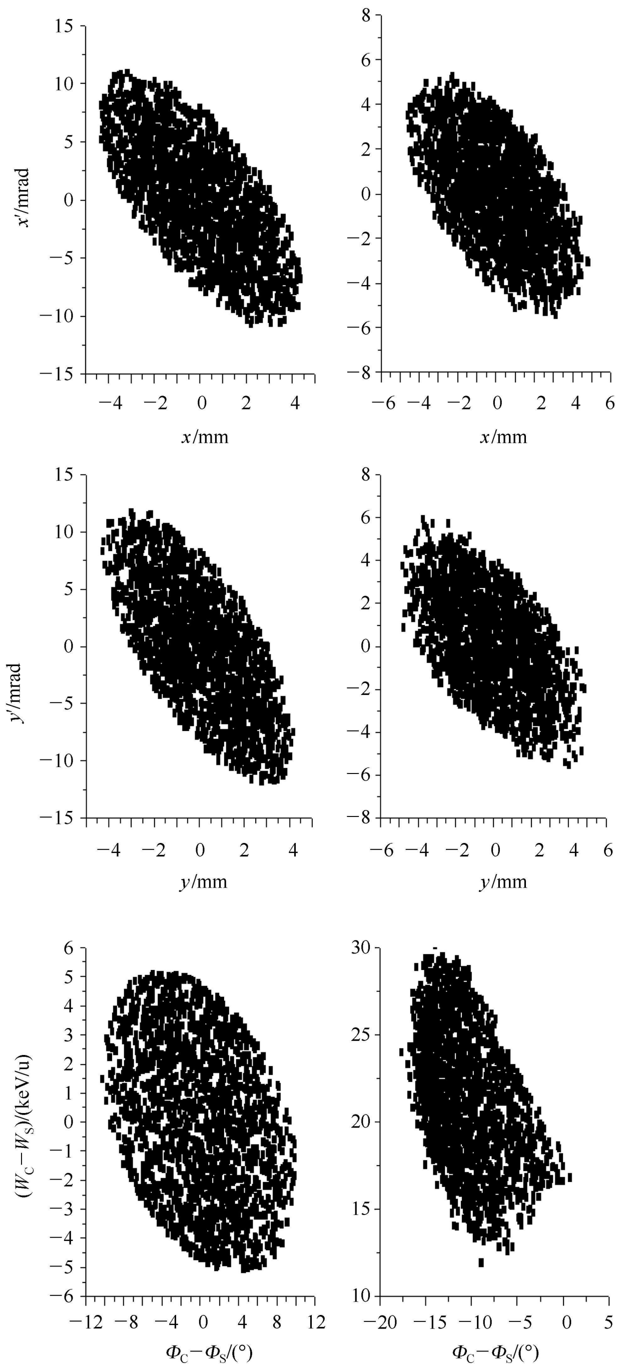

Fig. 2. Input particles distribution (100%) (left) and exit particles distribution (100%) (right).

5.0 emA are shown in Fig. 4. Fig. 4(a) and 4(b) show that the bunched beam center has the same kinetic synchronous energies and synchronous phases with the designed one inside three of the rebuncher drifting gap sections. However the kinetic beam energy at the bunched beam center is a bit higher than that at any gap center for all KONUS zero degree drifting tube sections and triplet lenses, which brings a matched phase slip against the

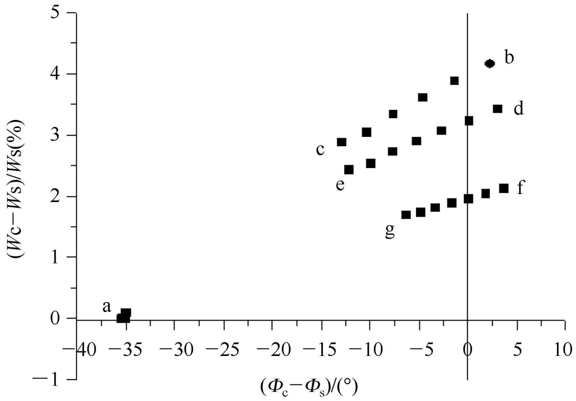

Fig. 3. The energy spread and synchronous phase at every accelerating gap (from ‘a’ to ‘g’).

zero degree synchronous particles. The dashed line in Fig. 4(b) shows the phase distribution of the bunched beam center particles. Fig. 4(c) and 4(d) shows the transverse beam envelopes are less than 4.6–6.0 mm within the resonators and up to 7.2 mm within the lenses. The beam aperture diameter of the triplets is 24.0 mm and the drift tube sections with inner aperture diameters are 18.0–20.0 mm. The zero degree synchronous phase section in IH-DTL compared to traditional negative phase that is kept in the Alvarez structure has a weaker radial defocusing effect and higher longitudinal energy gain. In addition, the bunching in negative synchronous phase and focusing in triplet makes the bunched particles stable in three planes and brings less emittance growth. Fig. 5 gives the result of the normalized emittance growth, which is about 8.0%. Fig. 6 represents the transmission efficiency as a function of input beam current.

3 Discussions of the principal parameters

3.1 Acceleration gradient

The effective voltage of accelerating gap is shown in Fig. 7. Because of the different RF ramping at both ends of the cavity, and the RF coupling of triplet between neighboring two adjacent 0 degree KONUS sections, the effective accelerating voltage for these gaps is set as half of the normal RF amplitude. The difference between the measured and designed effective gap voltage distributions will be tuned by the cavity tuning. In order to tune conveniently, an approximately constant maximum on-axis electric field along the whole structure is initially

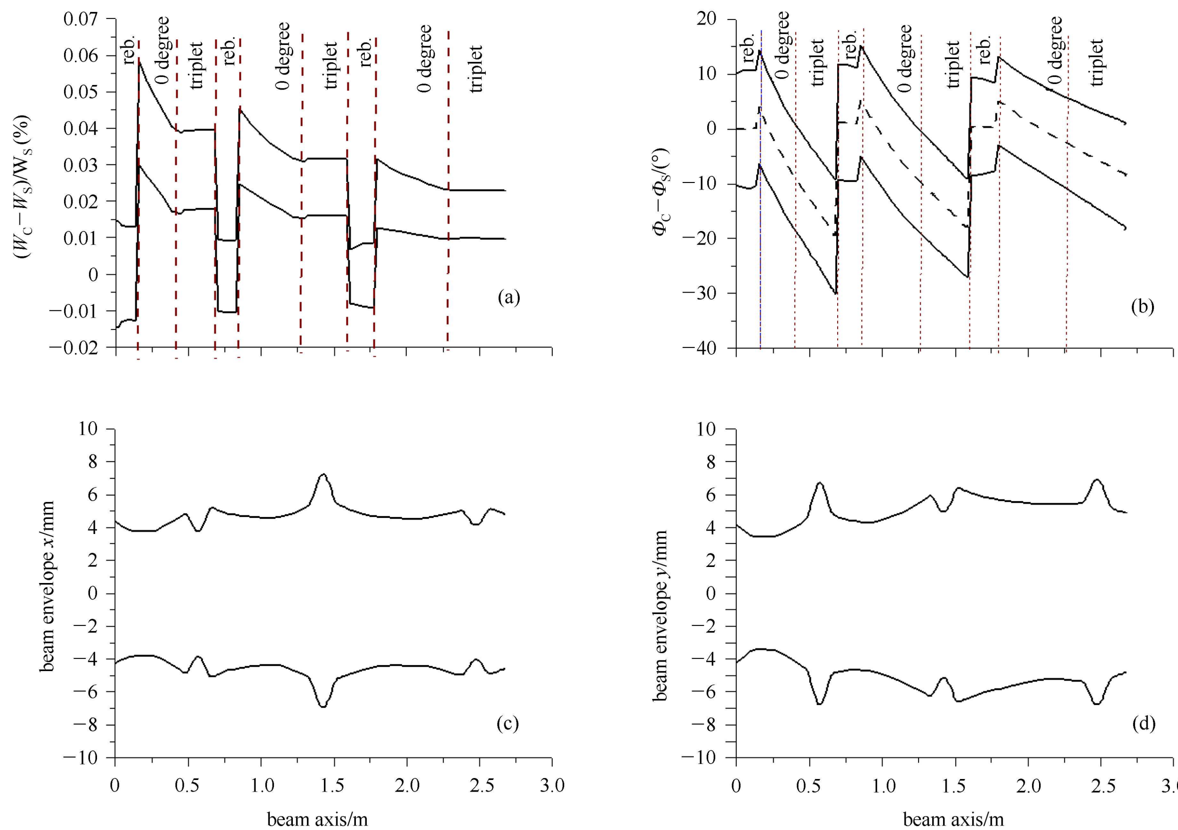

Fig. 4. 100% envelopes in three directions.

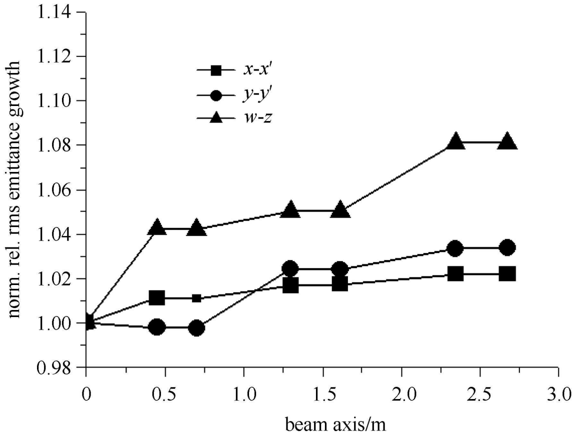

Fig. 5. Normalized RMS emittance growth.

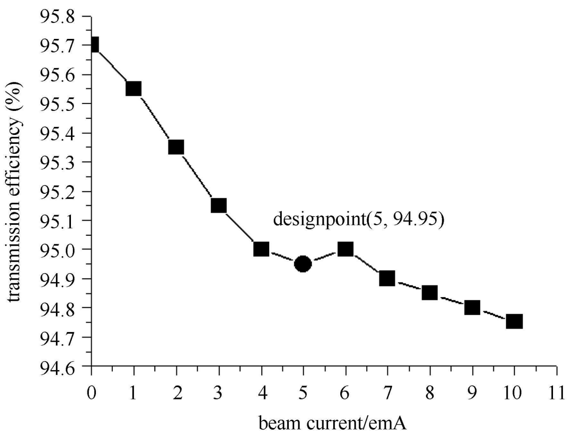

Fig. 6. Beam transmission efficiency.

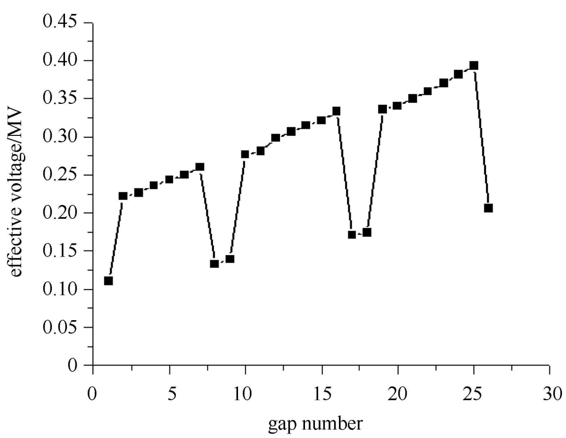

Fig. 7. The effective voltage in accelerating gap.

designed. With the increase of the gap length, the gap voltage distribution is ramped from about 260 kV at the low-energy end to about 393 kV at high energy end. The maximum value of axis field is shown in Fig. 8. A GSI High Current Injector (HSI) [12] has operated at the resonance frequency of 36 MHz since 1999, proving an average acceleration gradient about 4.3 MV/m for $^{238}U^{4+}$. Up to now, the duty factor of IH-DTLs is up to a maximum of 50%. The 108 MHz IH-DTL of GSI High Charge State Injector (HLI) [13] proves that there is an average acceleration gradient of about 2.63 MV/m with a duty factor of 50%. In our design, because of the requirements of CW mode operation, the design value of the averaged acceleration gradient along cavity is about 2.48 MV/m. The maximum value of axis field is 10.2 MV/m. Meanwhile, the Kilpatrick breakdown field is 10.56 MV/m at 81.25 MHz.

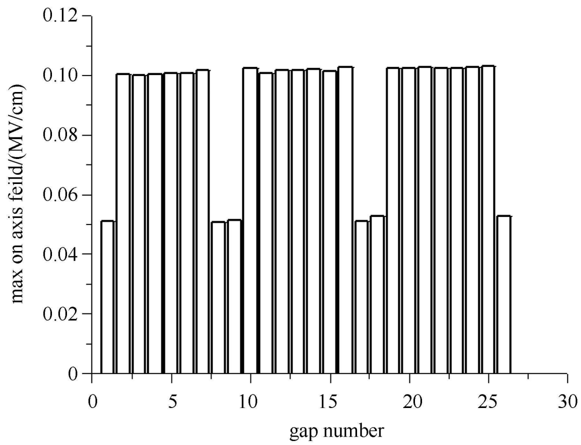

Fig. 8. The maximum value of axis field.

3.2 Quadruple field strengths

The parameters of magnetic quadruple triplet lens are listed in Table 2. Two quadruple triplets (QT1 and QT2) are placed in the IH-DTL to divide the IH-DTL into three accelerating sections. For the longitudinal motion, the lens acts like a drift space and must be as short as possible. Shorter powerful quadruple triplet lenses are needed for sufficient transverse focusing and minimum longitudinal bunched phase expansion. Pole tip fields up to $B_{\max}$=1.3 T are available with conventional technology (room temperature, laminated cobalt steel alloys) [5]. In the GSI HSI project [8], the aperture of triplet varies from 30 mm to 45 mm, the corresponding field gradient is from 74 T/m to 50 T/m, and the pole tip filed is about 1.12 T. In our case, the maximum quadruple field gradient is 98 T/m, and the corresponding pole tip magnetic field is 1.176 T.

3.3 H-type structure

IH-DTL has a very high effective shunt impedance,

Table 2. Quadruple lens parameters.

triplet lenses	QT1	QT2	QT3
Drift. length/mm	20/20	20/20	20/20
Eff. length/mm	44/79/44	46/84/46	46/90/46
field gradient/(T/m)	96/ 98/96	88.5/92/88.5	93.5/90/93.5

which leads to a shorter cavity length and less power consumption. The CH-structure has an excellent mechanical strength and it is convenient for water cooling with respect to CW operation mode; however, the dimension of CH-structure is too large at 81.25 MHz. The cooling design for IH-DTL is the key point for the structure design. This will be simulated by the CST studio in the near future.

4 Conclusions

A compact KONUS beam dynamics design for the low β IH-DTL of $^{238}U^{34+}$ beam is preliminary investigated with LORASR code. It will accelerate 5.0 emA $^{238}U^{34+}$ beams from 0.35 MeV/u to 1.30 MeV/u by an 81.25 MHz IH-DTL cavity. It achieves a transmission efficiency of 94.95% with a cavity length of 267.8 cm. The optimization has made the emittance growth only by about 8.0%. The designed average acceleration gradient is about 2.48 MV/m.

The authors would like to thank Prof. U. Ratzinger at Frankfurt University and Prof. Li Zhihui at Sichuan University for their kind help and useful discussions.

References

1 Kolmiets T E, Tretjakova S G, Yaramishev et al. The RFQ design software DESRFQ, ITEP/ANL Technical Note, 2005
2 Ratzinger U, Tiede R. Nucl. Instrum. Methods A, 1998, **415**: 229–235
3 Ratzinger U. H-type Linac Structure. CERN Accelerator School, Lufthansa Training Center, Germany, 8–16 May
4 Ratzinger U, Tiede R. Laser and Particle Beams, 2002, **20**: 447–450
5 Tiede R, Ratzinger U, Podlech H et al. KONUS Beam Dynamics Designs Using H-MODE Cavities. Proceedings of Hadrons Beam 2008, Nashville, Tennessee, USA: 2008
6 Ratzinger U. The IH-Structure and its Capability to Accelerate High Current Beams. Proceedings of the 1991 IEEE Particle Accelerator Conf., San Francisco, 1991, 567–571
7 Barth H, Dahl L, Hofmann S, Tinschert K et al. Unlac-upgrade Programme for the Heavy Element Research at GSI-SHIP. Proceedings of EPAC2006, Edinburgh, Scotland. 2006
8 Ratzinger U. High Current IH Structure. Proceedings of the EPAC 1994 Conference. London, 1994, **1**: 264
9 Ratzinger U. The New High Current Ion Accelerator at GSI and Perspectives for Linac Design Based on H-Mode Cavities. Proceedings of the EPAC 2000 Conference. Vienna, Austria, 2000, 98–102
10 LU Yuan-Rong. Development of an IH-DTL Injector for the Heidelberg Cancer Therapy Project. Peking University, 2005. China
11 Ratzinger U et al. LORAS–A computer code to calculate the longitudinal and Radial beam dynamics of a drift tube accelerator. GSI internal report 0791
12 Ratzinger U. The New GSI Prestripper Linac for High Current Heavy Ion Beams. LINAC 96. Geneva, Switzerland, 1996, 288
13 Klabunde J. High Charge State Injector for GSI. Proceedings of the 1992 Linear Accelerator Conference. Ottawa, Ontario, Canada, 1992